1.8.

[redacted]

CR 55-039

T- **A SURVEY OF ADAPTIVE COMPONENTS**

FOR USE IN FAILURE-FREE SYSTEMS Special Technical Report No. 1

UNPUBLISHED PRELIMINARY DATA

CNASA Contract Nasw-572

Reference WGD-38521

August 1963

9431008

Westinghouse Electric Corporation

Electronics Division

P. O. Box 1897 Baltimore 3, Md.

Special Technical Report No. 1

on

A Survey of Adaptive Components

For Use in Failure-Free Systems

Contract Nasw-572

Reference WGD-38521

August 1963

[redacted]

The Westinghouse Electric Corporation

Electronics Division

Box 1897, Baltimore 3, Maryland

APPROVED: S. E. Lomax, Director
Advanced Development Engrg.

[redacted]

TABLE OF CONTENTS

Introduction

The Adaline Neuron[1] is an adaptive logic device which may be trained to recognize certain classes of input patterns. The device output is a binary signal which classifies particular combinations of input signals into two categories. An output decision is determined by a threshold element whose input is the linear sum of the products of each input and its associated variable weight. During adaption the weights are appropriately changed in order to make the output decision agree with the desired response. By following a simple set of rules after each application of input signal combinations the device is caused to converge to an optimum state for properly categorizing the set of input patterns.

Although training rules for a single layer system have been formulated by Widrow[1,2] new adaptive theory is required if systems of two or more cascaded layers are to be properly trained to perform complex functions of adaptive behavior and pattern recognition. The question of whether such devices may be connected in complex arrays and demonstrate brain-like behavior has generated considerable interest. Such applications appear to be philosophical and subject to considerable controversy. Of primary concern in the present study is to consider the usefulness of the Adaline neuron approach in implementing the adaptive voting elements of a redundant system.

The chart of Figure 1 shows how adaptive voters may extend the reliability of a conventional redundant system, allowing a system using 9 replicas to outperform a conventional system using 35 replicas of each function.

The Adaline neuron has received considerable quantitative study in application to pattern recognition. When modified as shown in Figure 2, and applied as an adaptive voter, the training rules become quite simple since the desired output is determined by a voting of the weighted inputs. Initially, all weights (gains) are made equal. The decision element will then provide an output in accordance with the states of the majority of binary, replicated input signals. If input errors are independent and random the adaptive voter, by progressively adjusting its weights to assign high weights to reliable inputs and low weights to failed or unreliable inputs, may derive correct information from a small minority of correct inputs.

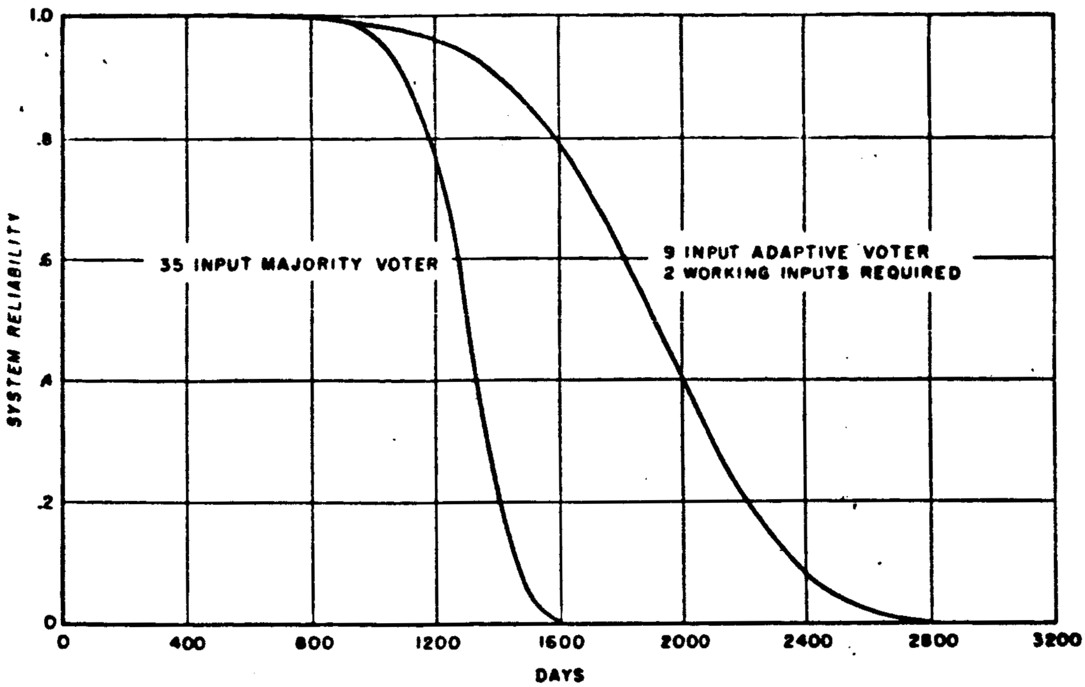


Figure 1 Comparison of Adaptive and Majority Voting Techniques

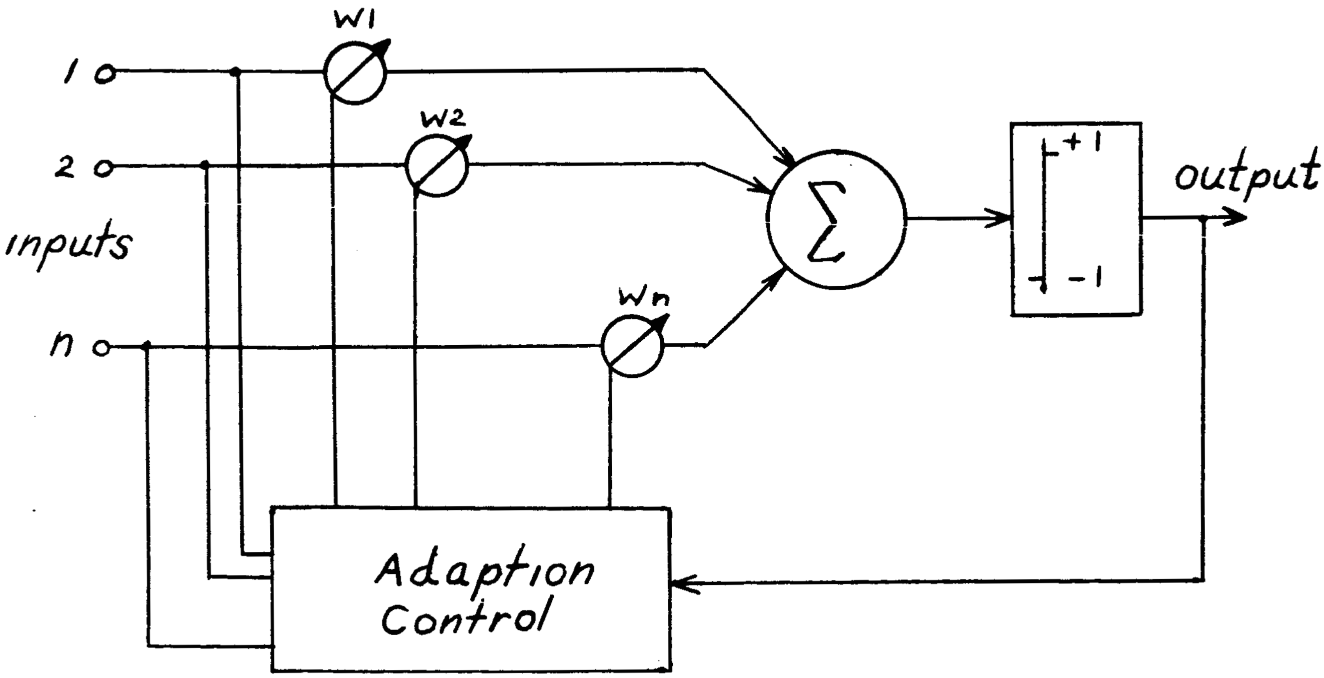


Figure 2 Adaptive Voter

In this manner the effect of errors caused by input failures may be negated, allowing a correct decision to be made under a high probability of input signal failure. The simple, fixed majority voter will make output decision errors when more than half of the inputs fail or are in error. The adaptive voter, by masking out input errors as they occur, may tolerate failures until only two correct inputs out of the original group are present.

In order to provide automatic adaption it is necessary to continuously compare the output decision with each binary input and to incrementally decrease or increase each input weight according to whether agreement or disagreement exists. Assuming that input errors or failures occur randomly and that the automatic adaptive process can negate an unreliable input before other failures occur, the adaptive voter offers the possibility of realizing system reliability of unprecedented excellence.

Inherent in the basic design of an adaptive voter is the requirement for a variable weighted device which performs integration and displays relatively permanent memory. These special characteristics have stimulated considerable effort toward the development of suitable adaptive components. Devices which display variable weight with memory generally utilize phenomena involving atomic translation or rotation. The following represents a survey of the more promising techniques which have been suggested by researchers. The first three devices described exploit electrochemical effects while the remaining devices utilize magnetic domain phenomena.

1. Electro-Chemical Devices

a. The Memistor

The Memistor[3], an electrolytic device developed at Stanford University by Widrow, is an electronically adjustable resistor with a rate-of-change of resistance controlled by application of d-c current in a third electrode. It consists of a sealed plating cell containing an electrolytic bath, a resistive substrate upon which metal is deposited and a metal source electrode. A typical configuration indicating the placement of electrodes and electrolyte in a small plastic enclosure is shown in Figure 3. Two leads are attached to the substrate and resistance between these leads can be reversibly controlled by passing plating current into a third electrode. The conductance of the device is changed and stored by plating or stripping metal from the substrate by means of the integral of the plating current. Conductance is sensed nondestructively by applying a low voltage a-c signal and measuring the resultant current flow.

Normal d-c drop between between source and substrate is typically 0.2 volts at a plating current of 0.2 ma. The substrate resistance changes from 30 ohms to 2 ohms in 10 seconds with this magnitude of plating current. The AC sensing voltage applied is usually 0.1 volts RMS. A typical implementation of the Memistor with associated transformer coupled sensing and d-c plating circuitry is shown in Figure 4.

Although Memistors are commercially available at a cost of approximately \$50 per cell their application in a practical system is somewhat cumbersome. Transformer coupled circuits are usually required in order to present a balanced load to the plating current source, and to provide the

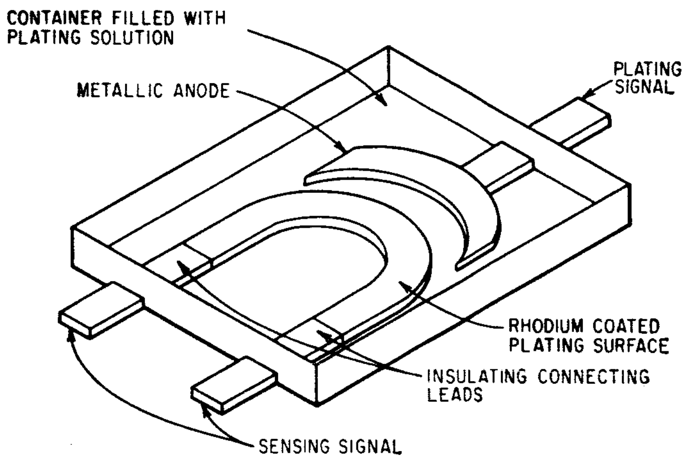


Figure 3 Memistor Cell

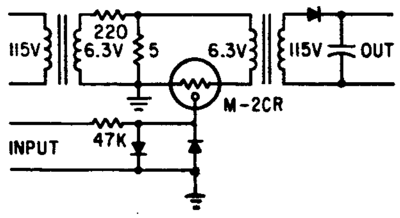


Figure 4 Memistor Integrator

low voltage drop across the substrate. The substrate resistance is usually less than 100 ohms and the a-c voltage drop must be kept below 3/4 volt in order to prevent the formation of gas in the cell. Some difficulty has been reported in keeping the substrate material free of dimensional imperfections which in turn cause non linear plating effects to take place. Long term stability is apparently affected by chemical reactions taking place between plating material and electrolyte. To date Memistors are available in sample quantities and it is difficult to predict ultimate large scale production costs, repeatability and reliability.

b. Solion

The solion is a fluid-state device which functions by controlling and monitoring a reversible electrochemical "redox" reaction. The term redox refers to a chemical reaction in which oxidation and reduction occur simultaneously. The redox system used in solions consists of two electrodes immersed in an electrolyte containing both the oxidized and reduced species of an ion. The system is completely reversible in that oxidation can occur at either electrode while an equivalent amount of the same element is reduced at the opposite electrode. Iodine is the reacting element most commonly used.

A simplified drawing of a solion tetrode and its output characteristics is shown in Figure 5a. The tetrode has a platinum electrode at each end of a glass tube and two perforated platinum electrodes separating the tube into three compartments. The reservoir, containing the input electrode, is the largest compartment. The integral compartment, containing the common electrode, is made very small so an equilibrium distribution of the iodine may be quickly reached. The compartment between the shield and readout electrodes serve to separate the two electrodes. The output characteristics of a solion Tetrode are similar to that of a vacuum tube pentode, and show a transconductance of 40,000 micromhos at an output current of 500 microamperes.

A Solion Tetrode connected as an integrator is shown in Figure 5b. By controlling the charge transferred between the two input electrodes, a change in conductivity proportional to the integral of the input current may be obtained between the output electrodes. In this manner the device may be utilized as an integrator, providing an output current proportional to the integral of the input current. Because of the concentration potential, the input impedance of the solion tetrode is in the order of 1000 ohms and therefore a relatively high impedance signal source is required in order to avoid integration errors. At constant temperature, the stability of solions is reported to be less than 1% over a period of several days.

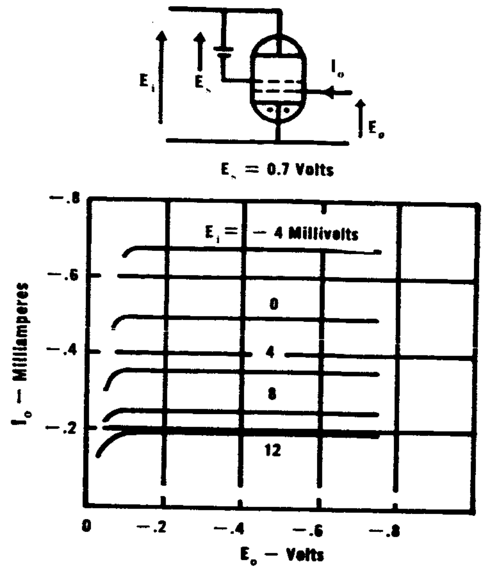


Figure 5a Solion Tetrode and Output Characteristics

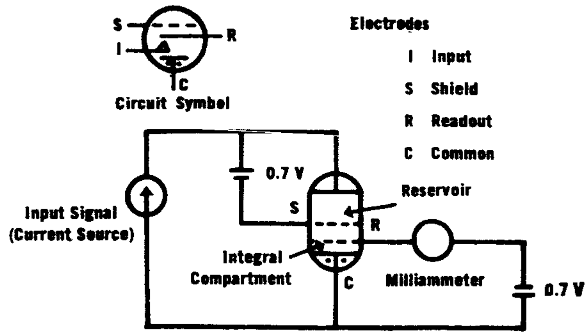


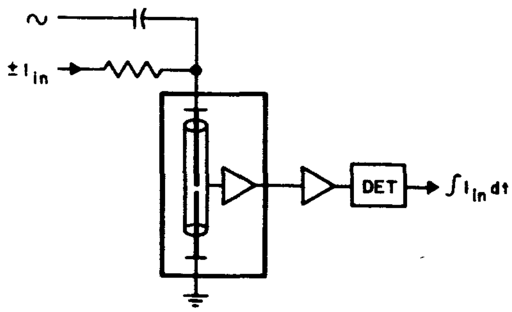
Figure 5b Solion Tetrode Connected as an Integrator

A practical problem in the use of solion tetrodes arises from the requirement of providing an isclated battery potential between input and shield electrodes to prevent iodine diffusion between the reservoir and integral compartments. Primary application for the solion tetrode to date has been demonstrated as a low level DC amplifier with a time constant of

20 seconds. Because of the inherent practical problems of precision design, isolated supply voltages and discharging effects of parallel outputs the solion appears to offer little promise as a practical adaptive component.

c. Mercury Cell

Another novel approach for variable gain with memory is achieved by use of a Mercury Cell integrator,[6] an electrochemical device which provides visual and electrical readout of the integral of an applied current. The integrating element consists of a capillary tube filled with two columns (electrodes) of mercury separated by a gap of aqueous electrolyte of metallic salt. Two different methods have been used to provide electrical read out. The first method called capacitive readout is shown functionally in Figure 6. The d-c input signal electroplates mercury across the gap at a rate which is a direct function of the input signal amplitude, thus causing the gap or bubble of electrolyte to move. The outside of the capillary is covered by a vapor-deposited conductive sheath. The mercury electrodes and sheath, separated by a thin glass wall provide a capacitance of approximately 20 pF. In application, an a-c signal is connected across the electrodes and



CIRCUIT DIAGRAM

Figure 6 Mercury Cell Integrator (Capacitive Readout)

superimposed on the d-c input signal. The a-c signal will divide in accordance with the capacitance existing between the upper mercury column and sheath, and the capacitance between sheath and lower grounded column of mercury. The excitation signal provides a signal at the sheath which is a direct function of the length of the ungrounded electrode. An auxiliary amplifier and detector in turn provide a proportional d-c signal of proper level to operate other related devices.

The device provides reversible integration, relatively stable memory, direct visual readout and a linearity better than 0.1 percent. Input control current is limited to ± 5 ma d-c. The integration time from minimum to maximum output signal is approximately 100 minutes at maximum control current. This time is ultimately limited by the maximum voltage which may be dropped across the electrolyte, without causing the formation of gas.

A typical capacitive readout integrator now commercially available is approximately 0.5 cu. in. but prices range around $130 per unit. Although displaying excellent stability and predictable operation such devices will require considerable price reduction before application becomes practical. The integration time although relatively long may not present a serious limitation for systems which display slow adaptive behavior as would be the case in adaptive voting elements.

Another technique for sensing the position of the bubble utilizes a light source and a photo-conductor whose resistance is inversely proportional to the amount of light passed by the transparent electrolyte. As the bubble moves out of line with the light source and photo-conductor target area the light becomes progressively blocked by the mercury columns, causing the photo-conductor resistance to increase. This technique allows faster integration because the bubble need only be displaced by its own height to effect a change from maximum to minimum light intensity at the photo-conductor. A typical photoelectric integrator commercially available occupies 1 cu. inch and requires 300 milliwatts to power an integral incandescent lamp. Output resistance varies over the range from 25K ohms to 350K ohms. Quantity prices are expected to fall below $15 per unit thus providing a reasonably inexpensive adaptive component. The use of an incandescent lamp for the light source imposes a serious life and reliability problem. The use of a more reliable light source and a substantial size reduction will be necessary before application becomes practical.

2. Magnetic Devices

Various techniques have been suggested for providing variable gain and non-destructive readout with magnetic devices. The phenomena utilized in such devices is based upon the ability of magnetic materials to store a remanent flux which is sensed in a non-destructive manner. Suggested devices provide the capability for a partial switching of magnetic domain under a volt-second impulse as the basic incrementing source. Suitable magnetic materials include ferrites and tape wound cores which are characterized by a square hysterisis curve. Most of the devices to be described utilize the same basic type of incrementing technique and differ primarily in the manner by which the stored flux is sensed.

a. MAD Integrator

A diagram of a typical multi-aperture device[7] is shown in Figure 7. In this device flux can be switched around the minor aperture by means of an a-c drive winding without disturbing the flux linking and stored around the main aperture. Initially the flux around the main aperture is set to cause saturation in either a clockwise or counterclockwise direction. A momentary reversal of the magnetizing force driving the main aperture will cause a partial reversal of the flux. The amount of flux reversal is determined by the magnitude and duration of the drive and the value of the hold current. The purpose of the hold winding is to retain a portion of the core saturated in the original direction of magnetization and thereby assure partial switching of the flux. The amount of flux alternately switched around the small aperture is then proportional to the flux which has been switched around the main aperture. The output voltage will consist of a signal whose voltage integral is proportional to the amount of flux trapped in the common area between the two flux paths. Several cycles of carrier drive may be required before this condition stabilizes. Care must be taken to limit the carrier drive to values less than the magnetizing force required to disturb the remanent flux around the main aperture.

The extent to which the remanent flux can be incremented is usually implemented by means of a smaller core of like magnetic material. The smaller core provides the appropriate amount of volt-second drive to increment the storage core in equal steps at various settings of remanent flux. Brain[8] has indicated that it is essential that incrementing should always occur at a constant reference phase with respect to the carrier drive unless carrier drive is removed. If this is not done the size of the incremental flux change will be dependent on the vector sum of the switching and carrier signals. A typical scheme for realizing integrator operation is shown in Figure 8.

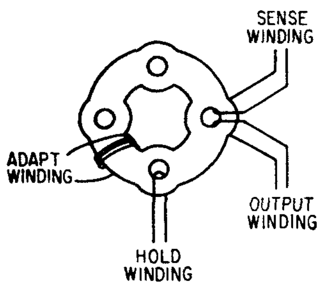


Figure 7 Multiple Aperture Device (MAD)

The physical requirement of providing a number of hand wound turns about the various apertures dictates to a large extent the cost of the device. Large driving currents, a moderate amount of timing during incrementing and relatively low output signal amplitude necessitate peripheral circuitry of considerable complexity. The resultant degradation in the basic reliability of the approach then becomes an imposing problem.

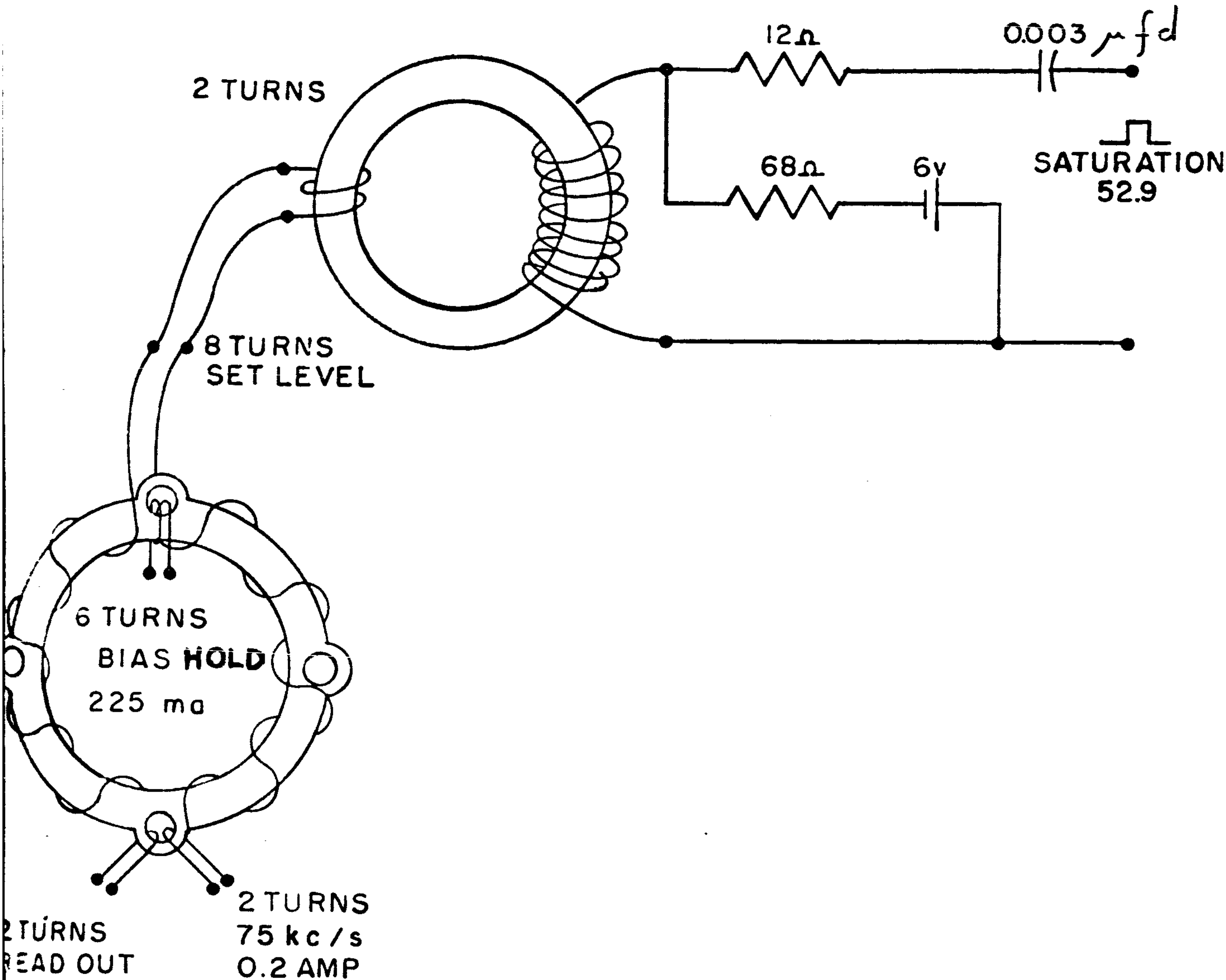


Figure 8 MAD Integrator

b. Orthogonal Core Integrator

The magnitude and direction of a stored flux may be sensed by applying a magnetic field orthogonally to the direction of stored flux.[9] This causes the remanent flux vector to rotate generating a voltage proportional to its rate of change and hence its magnitude. The application of a read or sensing field at right angles to the stored or written flux minimizes the interraction of the sense drive on the stored flux magnetic path. At the termination of the read drive the flux vector returns back to its original preferred orientation by virtue of domain elasticity. A typical orthogonal core configuration is shown in Figure 9. The flux level stored in the core is altered by pulsing the output winding in a manner similar to the incrementing techniques previously discussed. Output signal consists of either positive or negative pulses depending upon the direction of the stored flux, with an amplitude proportional to the magnitude of the remanent flux. Practical problems similar to those associated with the multiaperture device previously discussed again make physical implementation cumbersome.

c. Second Harmonic Integrator[10]

Nondestructive readout of remanent flux may be obtained by reducing the sensing drive to a value insufficient to cause irreversible switching. Since magnetic cores are generally non-linear the output voltage will contain harmonics of the drive current. In particular, the even harmonic

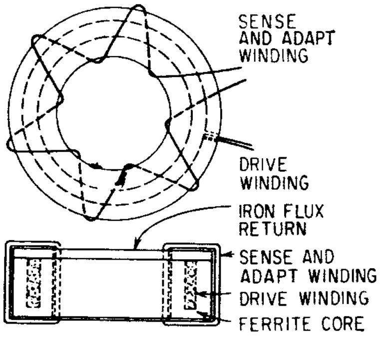


Figure 9 Orthogonal Core

voltage for certain core materials is found to be proportional to the net remanent flux level. The second-harmonic generator shown in Figure 10 consists of a pair of tape wound cores driven from an r-f sinusoidal power source. The output winding is arranged so that the fundamental component of drive voltage cancels out, leaving a second harmonic distortion voltage proportional to the remanent flux in the cores.

By passing a direct current through the output winding the remanent flux level may be altered. Due to an interaction between the d-c adapt current and the RF drive the rate of change of the remanent flux with respect to the adapt current is constant and reversible. Tape-wound cores have been found to provide the best performance and because of their higher permeability require fewer turns. Typical associated driving, sensing and timing circuitry tend to be rather elaborate however. The cancellation of the fundamental driving frequency is difficult to achieve in practice thus making the desired output signal appear against a background of noise. This low level signal must in turn be amplified in order to provide a signal compatible with the associated solid state circuitry which it must ultimately control. Clearly a separately switched driving source for each pair of cores is required in order to provide the individual binary signal inputs whose weights are to be altered. Since the sinusoidal drive currents tend to be in the order of 10 to 100 or more milliamperes the driving and peripheral circuitry is necessarily elaborate.

d. Magnetostrictive Integrator

The direction and magnitude of the net remanent flux in a magnetostrictive core may be sensed if the core is excited mechanically.[11] Figure 11 shows a simplified scheme for implementing a magnetostrictive storage system using an ultrasonic delay line to excite several magnetostrictive torroids. Driving source for the sonic delay line is a piezoelectric transducer. Input to each of the torroids is provided by means of narrow width

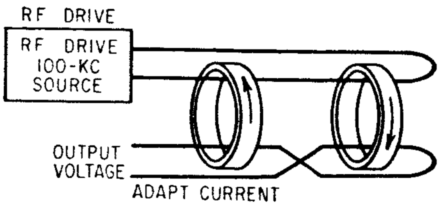


Figure 10 Second Harmonic Integrator

pulses through a separate write coil wound concentrically with the read coil. If the frequency and rms amplitude of the stress wave is maintained at constant value, the open circuit output of the read coil is approximately proportional to the flux stored in the individual torroids. Although this effect has been demonstrated experimentally by Nagy[11] and others the basic peculiarities of magnetic domain behavior especially under the influence of mechanical excitation is only crudely understood.

The experimental systems fabricated to date are rather large owing to the structural requirements of acoustical devices and the associated electronic circuitry necessary to provide proper timing, current driving and voltage amplification. At best considerable experimental work is necessary to show that magnetostrictive storage offers any real advantage over more conventional electro-magnetic approaches. Indeed, the sensing of remanent flux by acoustical means rather than by non-destructive, electrical drive appears to inject an unwarranted interface complexity.

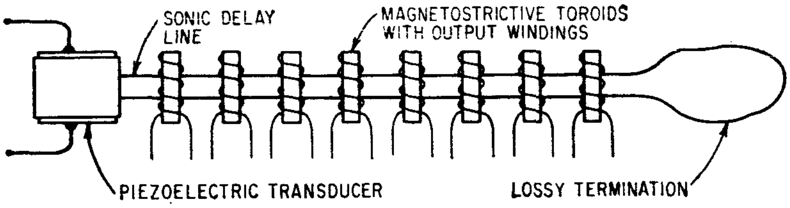


Figure 11 Magnetostrictive Integrator

3. Conclusion

As a result of the foregoing survey it became apparent that none of the suggested adaptive devices were sufficiently developed to justify the selection of a practical approach for immediate circuit implementation of an adaptive voter. An explicit evaluation was not attempted owing to the superficial treatment of the various devices by academic researchers.

The magnetic devices with their known sensitivity to temperature stress appear to offer the least hope for providing analog memory with long term stability. The requirement for providing carefully controlled incrementing with relatively large drive currents coupled with the small output signals and associated amplification appears to dictate an imposing amount of peripheral circuitry. The degradation in reliability as a result of this complexity represents a liability which makes practical application doubtful for redundant systems.

The electro-chemical devices, especially the memistor and solion in their present state of development, appear to be plagued by a number of stability problems. The memistor with its dependence upon an electroplating process which is not widely understood, chemical impurities and dimensional imperfections will require considerable refinement before application becomes practical. In addition the requirement for sensing the state of the device with an ac signal makes circuit implementation rather awkward.

Solions appear to be somewhat more practical if size is not an important consideration. It has been reported that the Rome Air Development Center is constructing an adaptive learning machine (CHILD) which uses 1080 solions. With its dependence on the chemical equilibrium of a redox system and the precise construction required to achieve stability the solion presents several challenging design difficulties. The requirement for providing an isolated battery cell between the input and shield electrodes imposes a practical encumberance on a system design which requires a large number of solions.

The mercury cell integrator with photoelectric readout appears in principle to offer the most attractive approach because of its simplicity, stability and general compatibility with conventional circuitry.

Since the output is essentially a variable resistance proportional to the integral of the control input current the device offers the possibility of providing a simple interface with standard circuitry. The mercury cell integrator is still in a rather primitive state of development and it is felt that any detailed circuit design undertaken at present would be premature. It has been reported that the Department of Defense is about to let a contract to develop and fabricate a large number of cells.

It appears reasonable then to restrict our efforts on the design of an adaptive voter to that of monitoring the state of the art in device development and to begin detailed circuit design when suitable cells become available.

References

1) B. Widrow and M. E. Hoff, "Adaptive Switching Circuits," Technical Report No. 1553-1, Stanford Electronics Laboratories, June 1960.

2) B. Widrow, "Adaptive Sampled-Data Systems - A Statistical Theory of Adaption," 1959 WESCON Convention Record, part 4.

3) B. Widrow, "An Adaptive 'Adaline' Neuron Using Chemical Memistors," Technical Report No. 1553-2, Stanford Electronics Laboratories, October 1960.

4) "An Introduction to Solions," Texas Research and Electronic Corp., Dallas, June 1961.

5) "D-C Amplifier Uses Fluid-State Tetrode," Electronic Products Magazine, October 1962.

6) "Capacitive Readout Integrator," Technical Brochure, Curtis Instruments, Inc., Mount Kisco, New York.

7) J. A. Rajchman and A. W. Lo, "The Tranfluxor," Proceedings of the I.R.E., March 1956.

8) A. E. Brain, "The Simulation of Neural Elements by Electrical Networks based on Multi-Aperture Magnetic Cores," Proceedings of the I.R.E., January 1961.

9) J. K. Hawkins and C. J. Munsey, "A Magnetic Integrator for the Perceptron Program," Annual Summary Report, Publication No. U-603, Aeronutronics, Newport Beach, Col., July 30, 1960.

10) H. S. Crafts, "A Magnetic Variable Gain Component for Adaptive Networks," SEL-62-147, Technical Report 1851-2, Stanford Electronics Laboratories, December 1962.

11) G. Nagy "Analogue Memory Mechanisms for Neural Nets," Cognitive Systems Research Program, Contract No. NONR 401(40), Report No. 3, Cornell University, Ithaca, New York, August 31, 1962.